

Traffic effect on soil compaction and yields of wheat in Spain

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Abstract

The general objective of this paper was to quantify the changes in the physical properties of an Aridisol soil and the effect on wheat yield due to agricultural tractors traffic in the Vélez Blanco District, Almería Spain. Parameters measured were cone index (CI) in the 0-600 mm depth profile, bulk density (BD) and rut depth; the variable wheat yields (WY) was measured too. The traffic treatments applied were: 0 (control plot), 1, 3, 5, and 7 tractor passes in the same tracks. Each experimental plot was trafficked with two tractors, one light (60 kN) and one heavy (80 kN). In topsoil (0-200 mm), up to five passes of the heavy (HT) and light tractors (LT), as in one and three passes, the BD and CI values responded to the ground pressure being higher in absolute value for LT. For the 200 to 400 mm depth range HT caused higher CI (1,570 to 2,200 kPa) and BD (1.38 to 1.68 Mg m⁻³) values than LT. Eight months later, WY was evaluated in tractor's track areas and decreases in the range of 18-38%, were measured. For seven passes the applications of total loads of 80 and 60 kN increased BD up to 1.5 Mg m⁻³ at depths of 200-600 mm. Although soil had high bulk density prior to traffic treatments, a significant increment of subsoil compaction still occurred due to the high traffic intensities applied.

Additional key words: axle load; bulk density; cone index; rut depth.

Resumen

Efectos del tráfico del tractor sobre la distribución de la compactación del suelo y los rendimientos de trigo en España

El objetivo general del estudio fue cuantificar los cambios producidos en las propiedades físicas de un suelo Aridisol y los efectos sobre el rendimiento del trigo debido al tráfico de tractores agrícolas en Vélez Blanco, Almería, España. Los parámetros analizados fueron índice de cono (IC) a una profundidad de 0-600 mm, densidad aparente (DA) y profundidad de huella; también se analizó la variable rendimiento del trigo (RT). Los tratamientos de tráfico aplicados fueron: cero (parcela testigo), y uno, tres, cinco, y siete pasadas de tractor sobre la misma huella. En cada parcela experimental se utilizaron dos tractores, uno ligero (60 kN) y uno pesado (80 kN). En el horizonte superficial (0-200 mm), hasta las cinco pasadas de los tractores pesados (TP) y ligeros (TL), los valores de DA y de IC respondieron a la presión en el área de contacto, siendo más alto en valor absoluto para TL cuando pasó una y tres veces. Para el rango de profundidad 200-400 mm, TP causó valores más altos de IC (1.570 a 2.200 kPa) y DA (1,38 a 1,68 Mg m⁻³) que TL. RT se evaluó ocho meses después sobre el área pisada, observándose una disminución en un rango de 18-38%. Las cargas totales aplicadas de 80 y 60 kN, con siete pasadas, aumentaron DA hasta 1,5 Mg m⁻³ en el rango 200-600 mm. A pesar de que el suelo presentó una alta DA antes de aplicar los tratamientos, se observó un incremento significativo de la compactación del subsuelo por las altas intensidades de tráfico aplicadas.

Palabras clave adicionales: carga en el eje; índice de cono; profundidad de huella; tráfico de tractores.

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Abbreviations used: Ap (cultivated horizon), BD (bulk density), CI (cone index), FWA (front-wheel assist), HPG (smaller tyre, higher pressure), HT (heavy tractor), LPG (bigger tyre, lower pressure), LT (light tractor), RD (rut depth), WY (wheat yields).

Introduction

Soil compaction is estimated to be responsible for the degradation of an area of 33 million hectares in Europe (Van Ouwerkerk and Soane, 1994). About 32% of the soils in Europe are highly vulnerable to subsoil compaction and another 18% is moderately vulnerable to subsoil compaction (Fraters, 1996). Compaction is caused by the high traffic intensity of tractors used for crop protection treatments and harvest operations, rather than for actual seeding, especially when these operations are carried out on wet soil or with high pressure tyres. Highly compacted soil, particularly in the surface layers, generates inadequate soil physical conditions for seedling emergence. When farm soils are compacted, the pore volume is reduced, aggregates crumble, and smaller inter-aggregate pores with non-accommodating faces are formed (Pagliai and Vignozzi, 2002). The major loss of the largest pores caused by soil compaction has the effect of changing the pore size distribution and hence water retention (Dexter, 2004).

Alakukku (1998) established that compaction induced changes in topsoil and subsoil (below 250 mm) properties were still measurable in clay and loam soils nine years after the traffic treatments were applied. The work also suggested that subsoils with a good natural structure could tolerate a single heavy loading and maintain a moderate structure, reducing the harmful effects of deep compaction. Håkansson and Reeder (1994) also found that the increase in vane shear strength in the subsoil measured one year after compaction remained nearly unaltered throughout an 11 year period in both sandy and clayey soils.

The soil parameters usually identified as the most critical in over-compacted soils are: aeration, bulk density and penetration resistance (Håkansson, 1987; Andrade *et al.*, 1993).

Narro-Farias (1994) advises that soil penetration resistance, in fine textured soil, should not exceed 1,000 kPa, because higher values can harm root growth. In this way Terminiello *et al.* (2000) found, in west Pampas region (Argentina), that cone index values over 1,150 kPa produced reduction, in the dry root weight, of cabbage crop (*Brassica oleracea* L.) in approximately 32%. Raghavan and McKyes (1979) state that dry bulk density values that exceed 1.05 Mg m⁻³ will cause yield reduction in clayey soils. Soza *et al.* (2003) found that, in the east Pampas region (Argentina) on a soil with high clay content, soil compacted

to a cone index values > 1,200 kPa reduced wheat (*Triticum aestivum* L.) emergence by 26%.

These results illustrate the potential for compaction to depress crop yields. Extremely dense soil impedes root growth and thereby limits water consumption of plants. Root responses to compaction may be complex due to the numerous ways in which compaction can modify the physical properties of soil. There have been many attempts to find critical values of cone index, soil strength or permeability that are related to root growth limiting factors.

Arvidsson and Keller (2007) studying the effect of wheel loads (11, 15 and 33 kN) at inflation pressures of 50, 70 and 150 kPa on soil stress, found that the tyre inflation pressure have a large influence on soil stresses measured at 10 cm depth, but have very little influence in the subsoil (30 cm and deeper). In contrast, wheel load have a very large influence on subsoil stresses.

Botta *et al.* (2002) considered that it is advisable to divide soil compaction into two different problems: i) topsoil compaction, within range of depth corresponding to the cultivated horizon (Ap), and ii) subsoil compaction, appearing at depths below the Ap depth limit. Håkansson and Reader (1994), who stated that when subsoil compaction is induced below the Ap horizon, mechanical loosening to alleviate this compaction is very difficult, always expensive and eventually impossible. In addition, these authors demonstrated that subsoil compaction, at the quoted depths, can cause lasting reduction in crop yields. In this regard data from research that compare yield effects in the presence and absence of random traffic on no-tillage soils are less extensive than those from conventional tillage systems. Campbell and Hunter (1986), working on imperfectly drained clay loam in Scotland, showed that even with fairly modest wheel loads, no-tillage yields were reduced when compared with not trafficked areas. However, this only occurred in the early years of no tillage and differences were absent by the fourth season despite no reduction in bulk density on the trafficked soil were found. In contrast, Botta *et al.* (2004) working with soybeans on clayey soil, found that yields could still be decreased by newly applied wheel compaction after 7 years of no tillage.

Tractor passes also cause soil compaction. Botta *et al.* (2006) reported that high traffic frequency (10 and 12 tractor passes in the same tracks equipped with 18.4-34 crossply tyre) of a light tractor (3.1 Mg) on Typical Argiudol soil in northeastern rolling Pampa region (Argentina, humid subtropical climate) produced

significant increases in cone index and dry bulk density in the topsoil and subsoil levels. Smith and Dickson (1990) cited several sources showing a direct effect of ground pressure on topsoil compaction, and total axle load on subsoil compaction.

Other specific references to traffic on non consolidated tilled soils were showed by Van den Akker (1998). Their experimental variable was wheel size and consequently different ground pressures were obtained matching different tyres to the same tractor. Both treatments were: LPG (bigger tyre, lower pressure) and HPG (smaller tyre, higher pressure). In topsoil, from 0 to 150 mm depth, the LPG system showed 40% diminutions of maximum pressure peaks, nevertheless at 550 mm depth, differences between both treatments became no significant. Therefore, the challenge is to attain a suitable seedbed while minimizing traffic-induced soil compaction, so that the physical properties of the soil do not diminish normal root growth (Botta *et al.*, 2004).

The general objective of this paper was to quantify the changes in the physical properties of an Aridisol soil and the effect on wheat yield due to agricultural tractors traffic in Almería, the southeast of Spain. Outlined hypothesis were: i) subsoil compaction distribution due to tractor traffic on recently tilled soils depends on total axle load and tractor passes; ii) topsoil compaction produced by tractor traffic depends on tractor passes and ground pressure.

Material and methods

The site

The experiment was conducted in the Vélez Blanco District of the Province of Almería in southeast Spain

(37° 41' N, 2° 5' W) at an altitude of 800 m a.s.l. (semi-arid climate). The no stone Class 2 Type 3 slope has a 30% gradient and is well drained (Drainage Class 3). The soil is an Aridisol (Soil Conservation Service, 1994), with an organic matter content ranging from 1.5% at the surface to 0.3% (w/w) at a depth of 0.6 m. Soil physical and mechanical properties are given in Table 1.

The site had been continuously cash cropped with wheat, barley (*Hordeum distichom* L.) and oat (*Avena fatua* L.) for 20 years prior to the experiment. Cultivation was with conventional tillage, including disks and a disk plow for fallow and seedbed preparation. To prepare for wheat, the site was disk plowed to 250 mm depth and then harrowed with a light disk harrow (vertical load 400 N disk⁻¹) before sowing. Soil moisture (w/w) during trafficking was 15.0% dry basis in the surface (0-200 mm), 16.1% at 200-400 mm and 16.0% at 300-600 mm. Proctor compaction test was conducted on soil samples obtained from the experimental area.

Experimental treatments

Five treatments were imposed on plots 100 m long by 7 m wide (700 m²) each one, where the experimental variable was traffic frequency of 0 (control plot), 1, 3, 5 and 7 tractor passes in the same tracks, with 3 m wide buffer zones between plots to avoid interactions. Plots were in completely randomized blocks having three replications. Each experimental plot were trafficked with 0, 1, 3, 5 and 7 passes of two tractors (Front Wheel Assist, FWA) equipped with single rear tyres: Light (LT) and Heavy (HT) (Table 2), tractors speed was 5.5 km h⁻¹. No hitch load was applied to the tractors during the experiment. These tractors were models usually

Table 1. Soil physical and mechanical properties at different depths (mm)

Proctor	A1	B21t	B22t	B3	C
	0-130	130-280	280-450	450-650	+650
Optimum water content (% w/w)	19.1 ± 0.16	22.1 ± 0.13	22.3 ± 0.20	23.2 ± 0.16	24.0 ± 0.18
Maximum dry bulk density (Mg m ⁻³)	1.41 ± 0.06	1.47 ± 0.05	1.51 ± 0.06	1.57 ± 0.02	1.60 ± 0.19
Soil organic carbon (kg ⁻¹)	8.6 ± 0.29	3.3 ± 0.2	4.1 ± 0.73	1.9 ± 0.56	1.7 ± 0.64
Total nitrogen (g kg ⁻¹)	1.30 ± 0.06	0.7 ± 0.03	0.8 ± 0.23	0.5 ± 0.01	0.6 ± 0.03
C/N ratio	6.67	4.71	5.12	4.0	2.83
Clay (< 2 m) (g kg ⁻¹)	140 ± 2.41	270 ± 2.41	240 ± 2.76	170 ± 1.99	140 ± 2.83
Silt (20-50 m) (g kg ⁻¹)	540 ± 4.62	530 ± 3.00	590 ± 3.32	720 ± 2.98	570 ± 1.81
Sand (g kg ⁻¹)	320 ± 1.57	200 ± 1.91	170 ± 1.92	111 ± 0.98	290 ± 2.01
pH in H ₂ O (1: 2.5)	8.0 ± 0.06	8.2 ± 0.02	8.2 ± 0.05	8.4 ± 0.02	8.4 ± 0.04

Table 2. Tractor characteristics

	FWA ¹	
	Heavy	Light
Engine power (CV kW ⁻¹)	155/113.6	120/88
Front tyres	480/70 R 28	320/70R 24
Rear tyres	580/70 R 38	
Inflation pressure, front tyre (kPa) ²	80	80
Inflation pressure, rear tyre (kPa) ²	100	120
Total weight (kN)	80	60
Front weight (kN)	32	24
Rear weight (kN)	48	36
Front tyre-soil contact area (m ²)	0.320	0.20
Rear tyre-soil contact area (m ²)	0.442	0.25
Ground pressure front tyre (kPa)	54.6	58.8
Ground pressure rear tyre (kPa)	57.3	70.6
Forward speed (km h ⁻¹)	5.5	5.5

¹ FWA: front-wheel assist². Inflation pressure was within the range recommended by the tyre manufacturer (Firestone).

used on commercial farms in the experimental area. The numbers of passes were selected in order to simulate the typical traffic intensity in the region under study. The intensity responds to the combination of load and number of passes of the used machinery in both tillage systems.

The tyre/soil contact area was measured by reversing or driving the tractor into the experimental field and spraying the area around the tyre with paint. A hydraulic lift was then used to raise the tractor so that the tyre track could be transferred onto a sheet of glass, and printed from there onto paper, and measured with a planimeter. Average ground pressure was estimated as the total axle load divided by the tyre/soil contact area for both tyres on the axle. Finally tyre widths were measured in the field under working conditions (Botta *et al.* 2008).

Statistical analyses were performed with the Statgraphics V. 7.1 program (Bitstream, Cambridge, MN, USA). An analysis of variance (ANOVA) was carried out, and means were analyzed by Duncan's multiple range test.

Soil response parameters

Soil water content (w/w), bulk density (BD), cone index (CI) and rut depth (RD) were measured on the same day and immediately following the traffic treatments. It is important to note that to measure the parameters CI and BD «zero reference» is not the soil

surface, it is located at a depth where there is no soil displacement. These parameters were measured on the bottom of the RD, in the centre lines of the tyre tracks, because in this zone the compressive effects tend to concentrate (Söhne, 1958).

BD and soil water content were measured with a gamma probe (Troxler, 3440), at different depth ranges (0-200, 200-400 and 400-600 mm) at 50 mm intervals along the tractor centre lines of tyre tracks. Each value of bulk density and soil water content was the average of ten measurements, all of which were verified by gravimetric data using a cylinder 100 mm high by 50 mm in diameter.

The CI was determined with a Rimick CP20 recording S313 penetrometer (ASAE, 1992). Twenty-five samples taken at a depth of 0-600 mm at intervals of 25 mm were averaged for each plot. Both BD and CI were measured at randomized locations on all plots.

Rut depth was measured using a profile meter consisting of a set of vertical metal rods (length 500 mm and diameter 5 mm), spaced at 25 mm horizontal intervals, sliding through holes in a 1-m long iron bar. The bar was placed across the wheel tracks perpendicular to the direction of travel and the rods positioned to conform to the shape of the depression. Rut depth was calculated using the average depth of 60 sets of readings.

The drilling date was 15 November 2008, and the fertilization rates were higher (approx. 150 kg ha⁻¹ NPK 8-16-8) than recommended ones. Weeds were controlled using post-emergence herbicides. Sowing rate was 95 kg ha⁻¹, depth sowing was 2 cm and the average of emergence was 89% for all treatments. Eight months after the traffic treatments were applied the wheat grain yield was evaluated, in the vehicle track. Wheat yields (WY) were measured in harvest (July 2009) using small quadrants. The wheat basis yield (control plot) was 1,100 kg ha⁻¹ in 2008 season.

Results and discussion

Effects of traffic tractor

For 1, 3 and 5 passes, rut depth was not significantly ($p < 0.01$) affected by ground contact pressure; average rut depths are shown in Table 3. No significant ($p < 0.01$) differences were found in rut depths between HT and LT when they passed one, three or five times, but there was a difference when traffic raised up to seven passes. H7 (152 mm rut depth) was significantly shallower

Table 3. Light (LT) and Heavy (HT) tractor rut depth measurements for one, three, five and seven passes

	Tractor and number of passes							
	L1	L3	L5	L7	H1	H3	H5	H7
Rut depth (mm)	77 ^a	79 ^a	95 ^b	120 ^c	70 ^a	72 ^a	88 ^b	152 ^d

Values with different letters in depth row show significant differences between treatments (Duncan's multiple range test, $p < 0.01$)

indicating that the compaction was more concentrated and severe in the top soil; the influence of rut depth on subsoil compaction is not clear.

In general, there were no significant differences ($p < 0.01$) in soil water content (Table 4) when penetrometer resistance (or cone index) was measured and correction or allowance for this was not considered necessary.

Figure 1 and Table 5 show that the values of BD and CI for all treatments are greater than the quoted values of 1 and 1.2 MPa cone index recommended by Narro-Farias (1994) and Terminiello *et al.* (2000) and the 1.05 Mg m⁻³ bulk density recommended by Raghavan and McKyes (1979), to avoid yield decreases. At 450 mm depth, the assessed CI values were again higher than the 1.5 MPa limited mentioned by Threadgill (1982) to avoid root growth retardance. Additionally Figure 1 shows that at all depths the soil bulk density increases with the number of wheeling and reaches always the

same value after 7 passes of 1.66 Mg m⁻³. This value even exceeds the Proctor (1933) density of this material (Table 1). The aggregate bulk density, however, initially increased but after 7 passes it was reduced again. In the deeper soil depth (400–600 mm) the aggregate bulk density tends to increase with the number of wheeling events.

Effects of ground pressure

In topsoil (0–200 mm), up to five passes of the HT and LT, as in one and three passes, the BD and CI values (Fig. 1 and Table 5) responded to the ground pressure being higher in absolute value for the LT. The LT used narrower tyres than the HT, which caused a higher pressure on the soil (70.6 kPa) of the LT compared with the HT (57.3 kPa). This is confirmed because, until fifth pass, as shown in Figure 2 the LT caused in both soils higher values in CI and BD than the HT, also in this figure, for heavy and LT, it can be seen that there is a strongly positive relationship between tractor passes and CI and BD values.

In this depth range, BD and CI always increased with the number of passes, but BD tended to be less responsive than CI. Whereas BD increased $\leq 20\%$, the corresponding average increase in CI was 390%. It is important to note that the soil deformation caused by repeated tractor traffic (each corresponding to a single wheel pass) was higher for the first than for the subsequent passes.

The behaviour of soil in this freshly tilled horizon following traffic agrees with results quoted by Smith and Dickson (1990) and Botta *et al.* (2002, 2006), confirming the direct relationship between topsoil compaction and ground pressure. Also, when soils are dryer, like in this case, the water potential is lower, and narrower tyres will cause more soil compaction than wider tyres (Greene and Stuart, 1985). As a result, narrower tyres are expected to cause higher statistically significant soil compaction at this water content than wider tyres (Froehlich *et al.*, 1980).

Table 4. Soil water content (w/w) when penetrometer resistance (or cone index) was measured.

Depth range (mm)	Soil water content ¹
0–50	19 ^a
50–100	19 ^a
100–150	18 ^a
Average (0–150)	18.6
150–200	19 ^a
250–300	18.7 ^a
300–350	19.3 ^a
Average (150–350)	19
350–400	20.2 ^a
400–450	20.4 ^a
Average (350–450)	20.3
450–500	20 ^a
550–600	20.6 ^a
Average (450–600)	20.3

¹ Different letters within each depth range indicate a significant difference for the different traffic treatments (Duncan's multiple range test, $p < 0.01$).

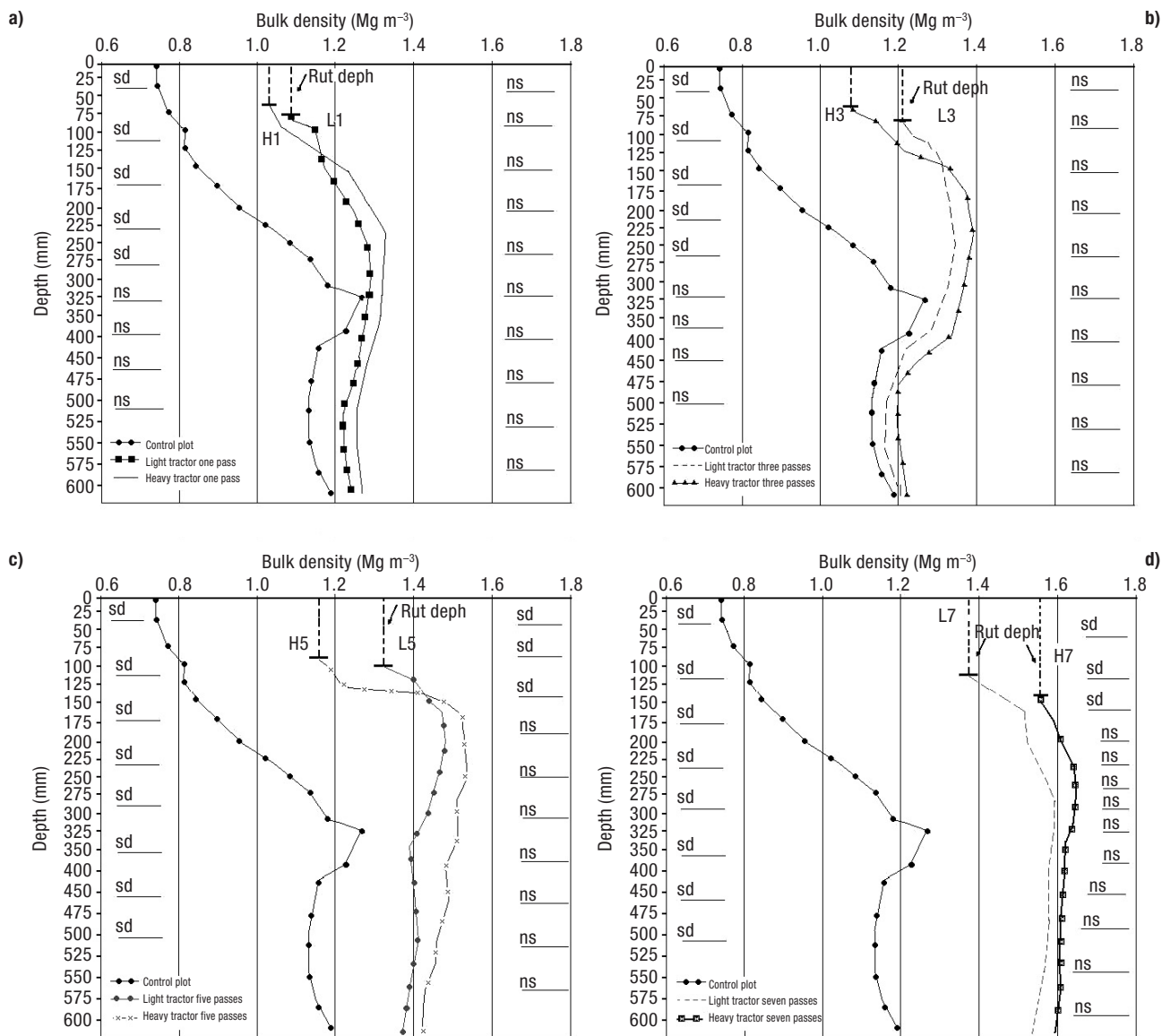


Figure 1. Bulk density (BD) values measured in the centerlines of the tyre tracks for different traffic treatments: 1 (a), 3 (b), 5 (c) and 7 (d) passes, respectively. sd: significant difference. ns: not significant (Duncan's multiple range test, $p < 0.01$)

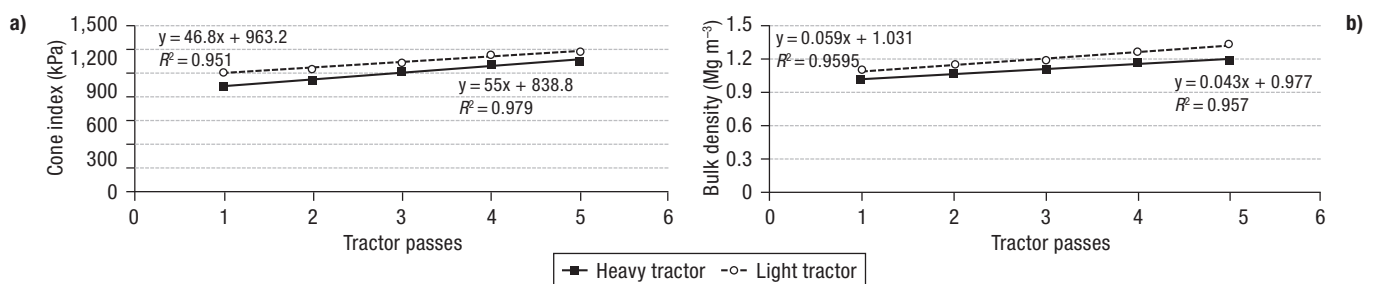


Figure 2. Relationship between cone index and tractor passes (a), and bulk density and tractor passes (b) for 0-200 mm depth range.

Table 5. Cone index (kPa) values measured in the centerlines of the tyre tracks for light (LT) and heavy (HT) tractors after one, three, five and seven passes in three depth ranges

	0-200 mm	200-400 mm	400-600 mm
Control plot	250 ^a	904 ^a	1,489 ^a
Tractor light one pass	1,010 ^c	1,207 ^b	1,542 ^a
Tractor heavy one pass	890 ^b	1,570 ^c	1,666 ^b
Tractor light three passes	1,089 ^c	1,330 ^c	1,536 ^a
Tractor heavy three passes	1,019 ^c	1,780 ^d	1,780 ^c
Tractor light five passes	1,180 ^c	1,490 ^c	1,610 ^b
Tractor heavy five passes	1,100 ^c	1,789 ^d	1,880 ^d
Tractor light seven passes	1,410 ^e	1,590 ^c	1,825 ^d
Tractor heavy seven passes	2,100 ^f	2,200 ^e	2,300 ^e

Within a column, values with different letters show significant differences among treatments (Duncan's multiple range test, $p < 0.01$).

It is important to consider that from the fifth pass, the superficial cone index values did not respond to the ground pressure, but were affected by the total load of the used tractor.

Effect of Axle load

Examination of soil responses to traffic in deeper layers (200 to 600 mm) revealed that soil compaction increased as the traffic intensity increased. This result agree with those quoted by Botta *et al.* (2002). For the 200-400 mm depth range, Figure 1 and Table 5 show that the HT caused higher BD and CI values than the LT. From this, it can be inferred that after a depth of 200 mm, tractor load was responsible for subsoil compaction, as demonstrated by Håkansson and Reeder (1994).

Data from both parameters (BD and CI) showed that compaction by tractor traffic caused considerable changes to the topsoil and subsoil properties. These results are similar to those of Håkansson (1987), who indicated that the lasting effects of compaction at high axle load are related to soil type, number of passes and number of years since compaction. Taking into account these results and the previous paragraph discussed, the hypothesis 1 and 2 are proved.

Effect on wheat yields

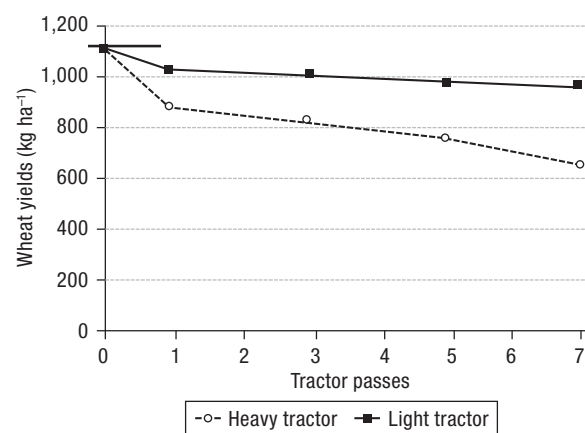
The effect of ground pressure and tractor passes on wheat yields reductions was found to be important; yields decreased when tractor traffic and total load increased. The applications of total loads of 80 and 60 kN increased bulk density up to 1.5 Mg m⁻³ at depths

of 200-600 mm in a Aridisol soil in Almeria. Significant ($p < 0.01$) difference was found in wheat yield for all tractor (HT and LT) passes as compared to the control plot, but treatments L5, L7 and all heavy treatments (H1, H3, H5 and H7), caused very significant reductions in yield.

The yield reductions in traffic lanes are shown in Figure 3. For HT the grain yield reductions were from 18 to 38% under normal weather conditions. Taking 2008 as the base year for wheat yield (control plot: 1,100 kg ha⁻¹), HT decreased this by approximately 18, 22.0, 30 and 38% for H1, H3, H5 and H7 respectively, and these agree approximately with those presented by Botta *et al.* (2004) and Jorajuria *et al.* (1997).

Conclusions

The applications of total loads between 80 and 60 kN increased bulk density up to 1.5 Mg m⁻³ at

**Figure 3.** Wheat yields (kg ha⁻¹) after different traffic treatments.

depths of 200-600 mm. However, up to the fifth pass of either the front-wheel assist (FWA) tractor ground pressure is responsible for topsoil compaction (0-200 mm). This leads to the fact that all the rut depth values measured for LT (up to the fifth pass) were higher than those measured for HT in spite of the difference in the weight and ground pressure of the tractors.

Although subsoil had high bulk density and cone index prior to traffic treatments, a significant increment of subsoil compaction still occurred due to the high traffic intensities applied. Repeated traffic in the same track, using light vehicles, below 50 kN axle load, produces subsoil compaction and wheat yields reduction.

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